SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	AMOC hysteresis in the EC-Earth model
Computer Project Account:	spitmec2
Start Year - End Year :	2021 - 2022
Principal Investigator(s)	Virna Loana Meccia
Affiliation/Address:	Institute of Atmospheric Sciences and Climate, National Research Council (ISAC-CNR), Italy.
Other Researchers (Name/Affiliation):	ISAC-CNR: S. Corti, J. von Hardenberg, P. Davini, K. Bellomo

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

Paleoclimate records suggest that freshwater input from the ice sheet melting into the North Atlantic produced abrupt changes in the Atlantic Meridional Overturning Circulation (AMOC). Those changes are believed to be linked to changes in the climate (Broecker et al., 1985; Bond et al., 1997; Rahmstorf, 2002; McManus et al., 2004; Clement & Peterson, 2008; McNeall et al., 2011), supporting the view of the classic bi-stability structure and hysteresis behaviour.

This special project (SP) has the main objectives of a) exploring the bi-stability of the AMOC in the EC-Earth3 state-of-the-art climate model, and b) studying the climate impacts of a reduced AMOC in the same model. To face this topic, we perform experiments of water hosing in the North Atlantic. Thanks to this SP, we participated in a model inter-comparison project with EC-Earth3 to study the AMOC hysteresis.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

During the project's first year, we ran additional experiments with respect to the originally proposed ones. On the one hand, we ran a pre-industrial (*piControl*) experiment because we needed some outputs unavailable in the existing *piControl* run. On the other hand, we extended the original runs of the water hosing perturbation. This was possible thanks to the collaboration with the SPITBELL special project.

During the project's second year, we slightly deviated from the original plan to deepen the study of the climate impacts of a reduced AMOC, particularly in the Euro-Atlantic region. Taking advantage of the water hosing experiments already run during the first year, we used 10-year slices of SST from different mean AMOC strengths as boundary conditions for AMIP experiments. We, therefore, run 20 ensemble members of 10 years each for three different mean AMOC index values: 17, 14, and 7 Sv (1 Sv = 10^6 m^3 s^{-1}). We saved daily outputs to study the impacts of a reduced AMOC on the blocking, weather regimes and extreme events in Europe.

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

The experience with the application and submission has been straightforward. Besides, the staff at ECMWF helped assist with any problems, particularly when I needed extra space to deal with model outputs.

Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

We report in what follows the results achieved so far regarding the two main aims of this SP:

a) Regarding the bi-stability of the AMOC in the EC-Earth3 climate model

Thanks to this SP, together with the collaboration of the SPITBELL special project, we participated in the North Atlantic Hosing Model Inter-comparison Project (NAHosMIP, Jackson et al., 2023). NAHosMIP aims to examine AMOC thresholds in CMIP6 models in the presence of freshwater forcing. We have used the CMIP6-generation EC-Earth version 3 in its standard resolution (T255 L91, ORCA1L75). The ocean component of EC-Earth3, NEMO, was modified to account for the idealized forcing of a freshwater flux (water hosing).

The experiments used a preindustrial control state as an initial condition, and two sets of experiments were run. The first set of experiments considers uniform water hosing of 0.3 Sv, and the freshwater perturbation is applied as an additional freshwater flux uniformly distributed over the region between 50°N in the Atlantic and the Bering Strait, as indicated in Figure 1a. The second set of experiments applies a more realistic freshwater flux around Greenland using the method of Gerdes et al. (2006), as shown in Figure 1b. A water hosing of 0.1 Sv is used for this set of experiments. In both cases, the forcing is applied for 20, 50 and 100 years, and then the perturbation is interrupted to leave the system freely adjust to its new equilibrium. This allows us to study the possibility of the system recovering its initial state.

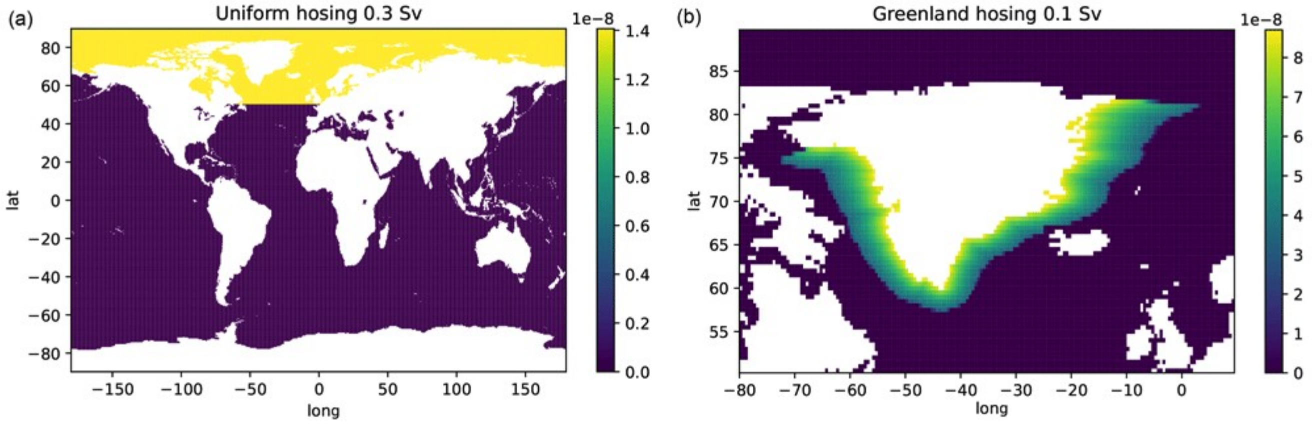


Figure 1. Hosing fields for the (a) uniform and (b) more realistic freshwater flux. Units are m s^{-1}. From Jackson et al. (2023).

Figure 2 and Figure 3 compare the results obtained with EC-Earth3 and the other climate models that participated in NAHosMIP for the first set of experiments, with the uniform freshwater flux of 0.3 Sv. All models show an AMOC weakening and shallowing as a response to the water hosing (Figure 2, middle column). In the recovery experiments where the hosing is stopped after 20 years, the AMOC recovers towards its control state in all experiments (Figure 3). However, in some experiments, the AMOC demonstrates hysteresis by remaining in a weak state for at least 100 years after 50 years of hosing (HadGEM3-GC3-1MM and CESM2), after 70 years of hosing (CanESM5), and after 100 years of hosing (IPSL- CM6A-LR).

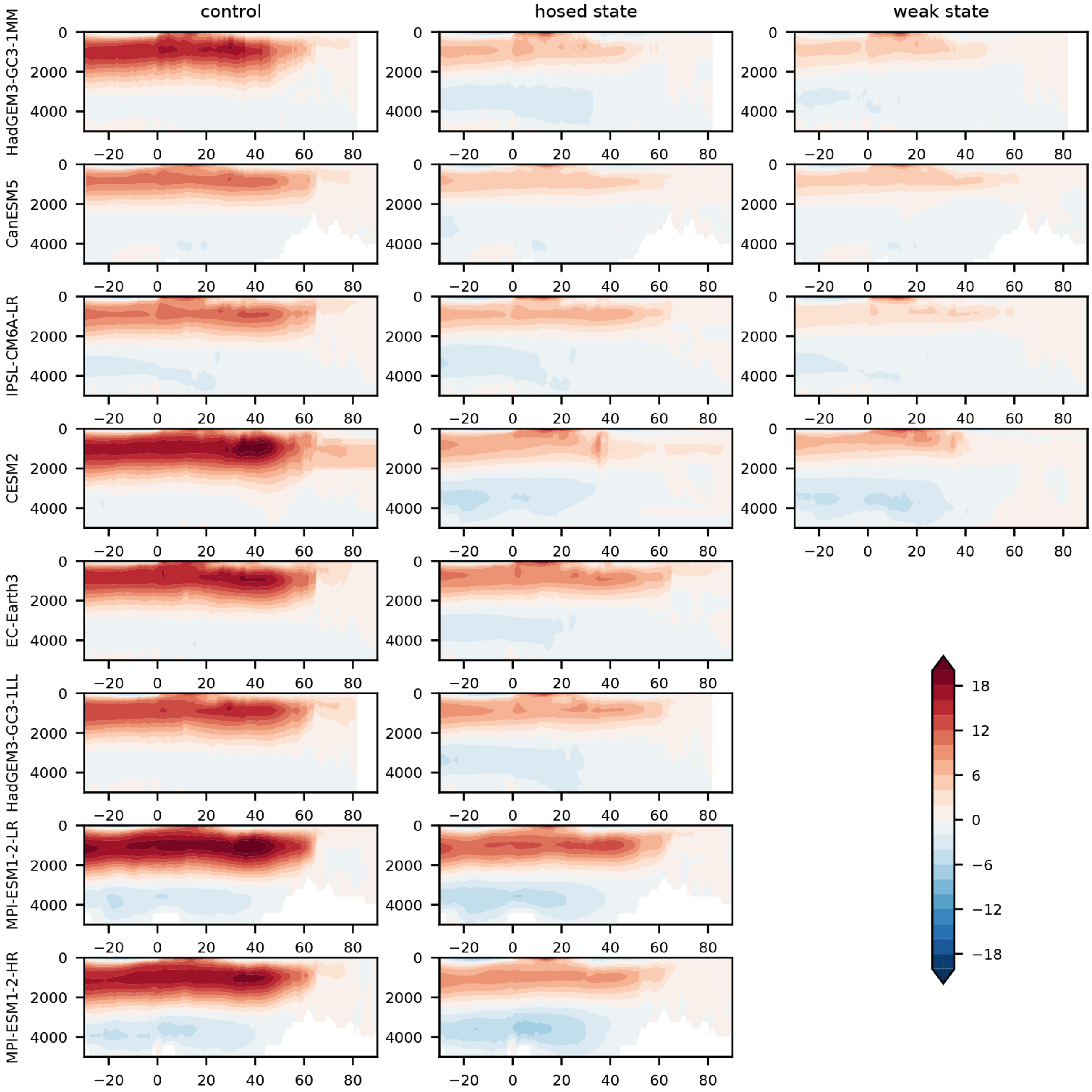


Figure 2. Time means stream functions (Sv). The first column shows the control, the second column shows years 40–50 for the uniform hosing experiments, and the third column shows years 50–100 of the recovery experiments where the AMOC stays weak. From Jackson et al. (2023).

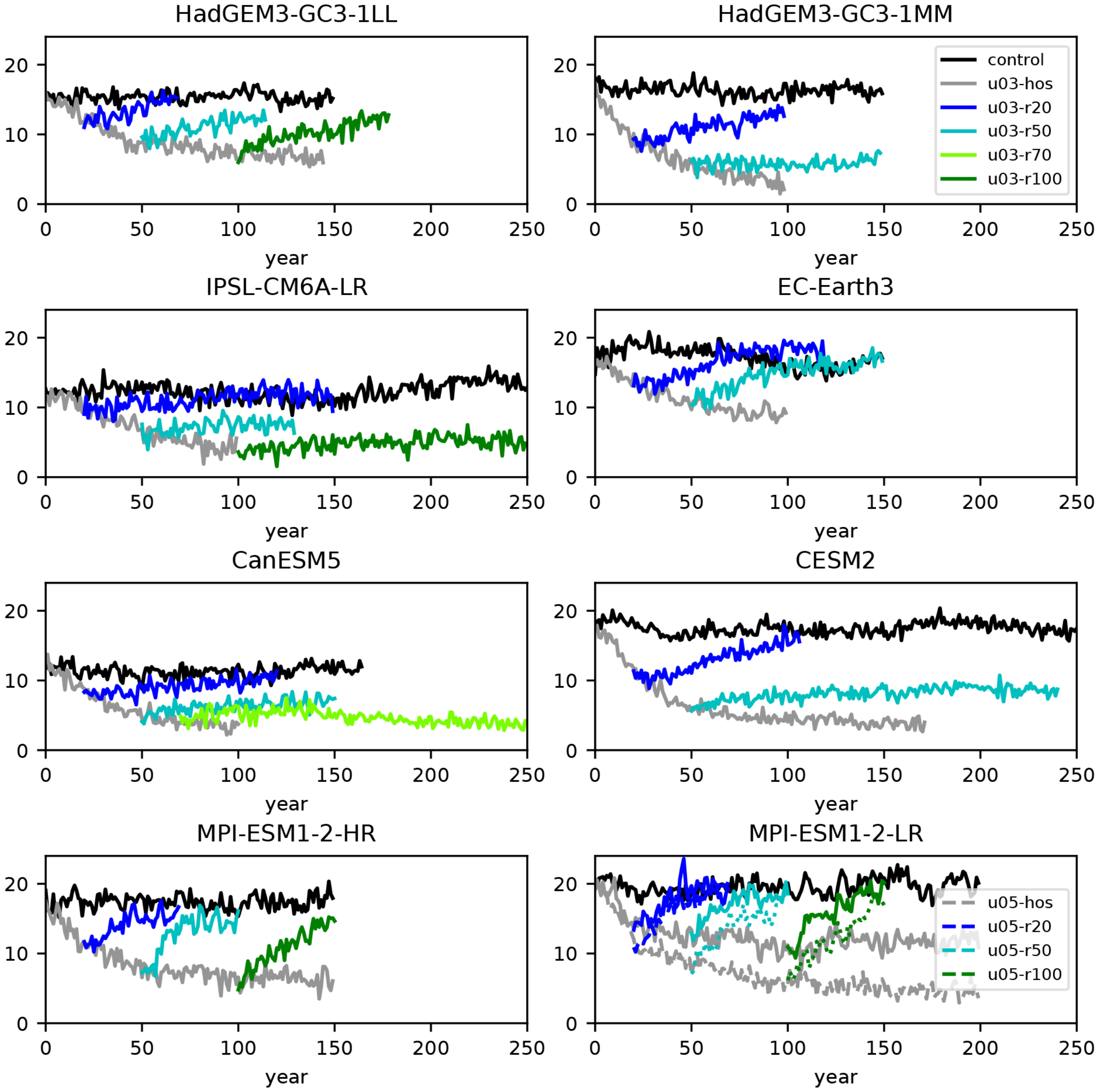


Figure 3. AMOC strength (maximum in depth at 26.5°N) for the uniform hosing experiments. Experiments are the control (black), the hosing activated (grey), the hosing stopped after 20 years (blue), the hosing stopped after 50 years (cyan), the hosing stopped after 70 years (light green), and the hosing stopped after 100 years (green). From Jackson et al. (2023).

The time series of AMOC strength for the second set of experiments in which the freshwater perturbation is more realistic (Figure 1b) are shown in Figure 4. The AMOC reduction in all experiments is smaller than in the previous experiments, likely because the rate of freshwater input is lower. A comparison of the AMOC weakening from both sets of experiments shows that those models with a stronger weakening due to one hosing scenario have a stronger weakening due to the other hosing scenario.

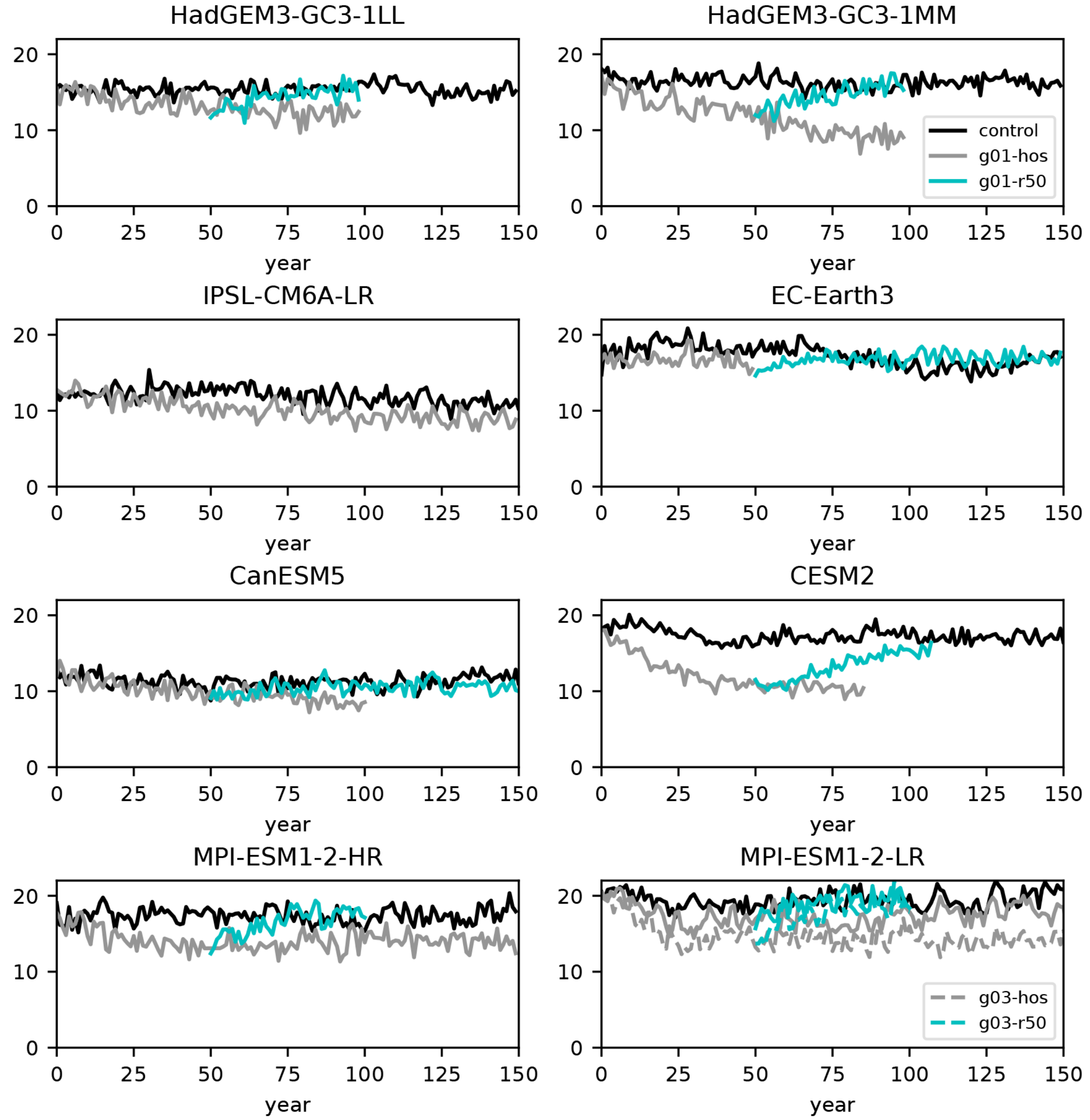


Figure 4. AMOC strength (maximum in depth at 26.5°N) for the more realistic hosing forcing. Experiments are the control (black), the hosing activated (grey), and the hosing stopped after 50 years (cyan). From Jackson et al. (2023).

In our case with EC-Earth3, the AMOC recovers, even if the water hosing is stopped after 100 years (not shown). Therefore, EC-Earth3 is resilient to the freshwater perturbation intended to reduce the AMOC. However, some models show a threshold where the AMOC does not recover after stopping the perturbation. The difference in model behaviour cannot be explained by the ocean model resolution or type, by details of subgrid-scale parameterisations, or by aspects of the mean climate state such as the strength of the salinity advection feedback, the location or depth of deep convection, or the position of the inter-gyre boundary. Instead, the AMOC behaviour appears to be related to the state the model reaches after hosing finishes; specifically, those experiments where the AMOC has reached the weakest states, where March mixed-layer depths are the shallowest, and where the eastern subpolar gyre and Nordic seas are the coldest and freshest with the greatest sea ice extent are those where the AMOC subsequently does not recover. For details on the mechanisms studied, the reader is referred to Jackson et al. (2023).

b) Regarding the climate impacts of a reduced AMOC in the EC-Earth3 climate model

Part 1

We further analysed the water hosing experiments with EC-Earth3 to investigate the impacts of an AMOC abrupt weakening on the winter climate variability focusing on the North Atlantic and Europe. In particular, we used the experiments with the uniform freshwater flux of 0.3 Sv. The model was run for 140 years with the water hosing activated. After this time, the hosing is halted, and the model is left to evolve freely for an additional 70 years, for a total experiment length of 210 years. Figure 5 shows the AMOC diagnostics for this experiment and a *piControl* experiment which is 150 years long. Years 100–159 of the water hosing experiment (shaded in Figure 5a) are those in which the low-pass filtered (10 years running mean) AMOC index is more than 50% weaker than the control simulation. Therefore, those years are compared to the 150 years control run.

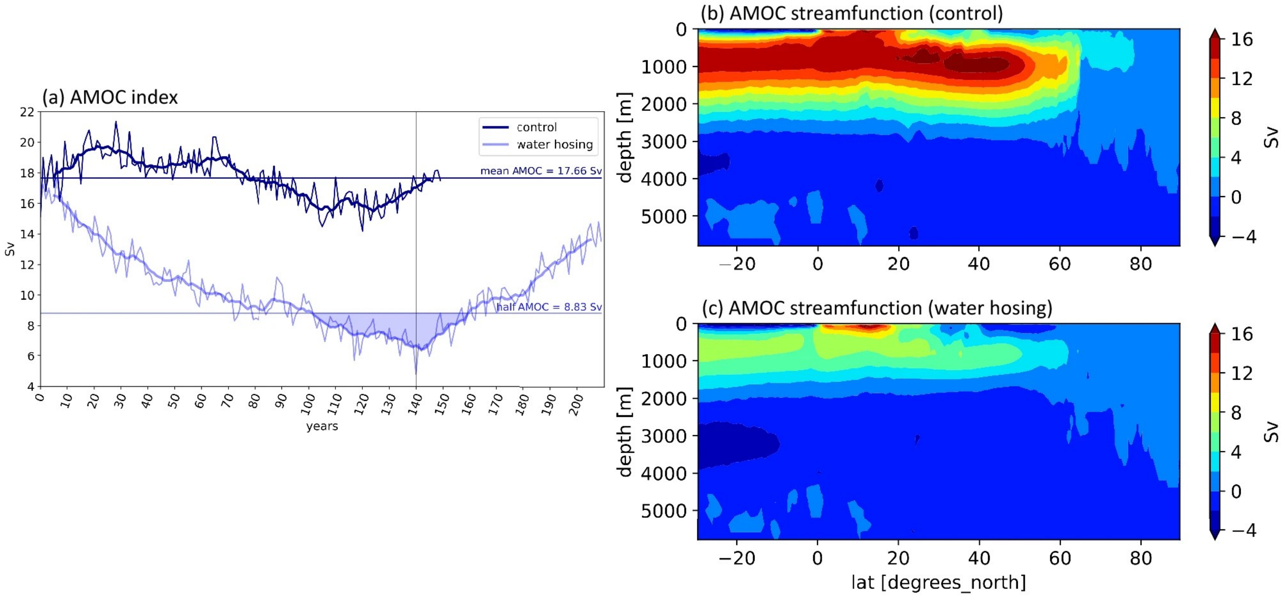
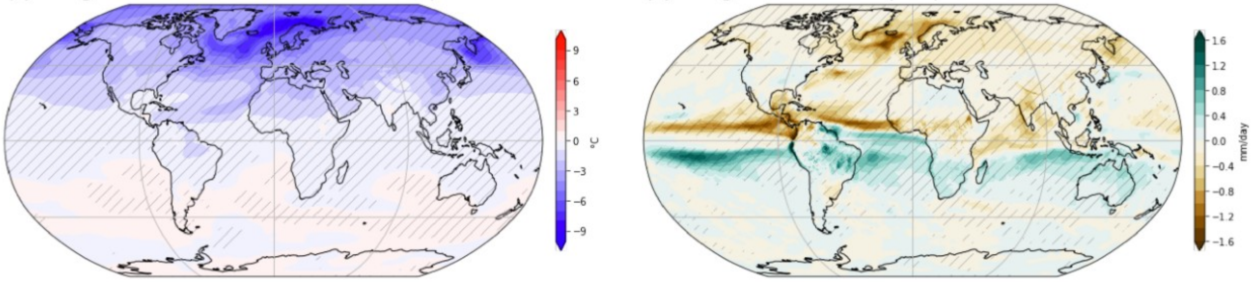


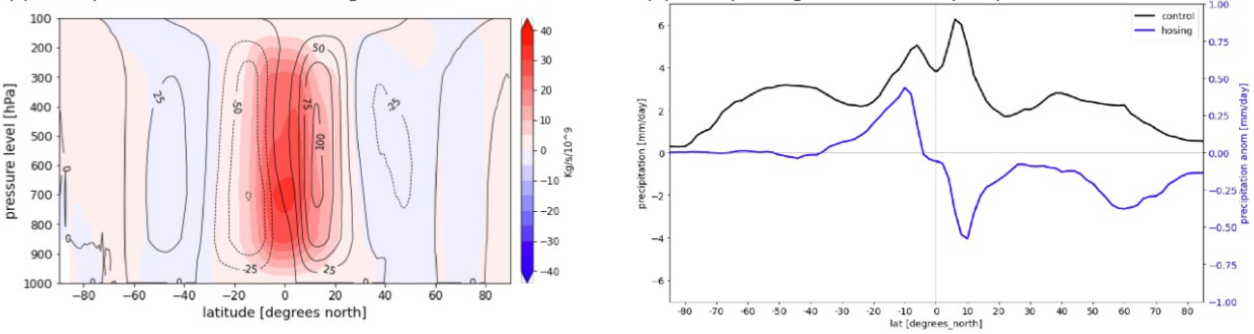
Figure 5. (a) time-series of the AMOC index (maximum strength of the overturning meridional streamfunction between 25.5°N and 27.5°N, and below 500 m) in the control and water hosing experiments. Superimposed to annual mean values are 10 years running averages of the time-series; and (b) and (c) mean of the ocean meridional overturning mass stream function in the Atlantic/Arctic sector for both experiments. From Bellomo et al. (2023).

The results regarding the changes in the mean climate due to an AMOC weakening are plotted in Figure 6 and confirm the ones from previous studies. For instance, the Earth cools due to the AMOC weakening and consequently a reduced meridional heat transport, particularly in the northern hemisphere (NH; Figure 6a). On the other hand, precipitation decreases over most of the NH (Figure 6b), especially over the North Atlantic, and tropical rainfall exhibits a southward shift in the zonal annual mean Inter-tropical Convergence Zone (ITCZ; Figure 6d). The southward shift of the ITCZ corresponds to a southward shift of the Hadley cell (Figure 6c) in the annual mean. These results evidence the important role of the ocean meridional heat transport due to the AMOC in regulating precipitation patterns.



(a) Change in annual mean near-surface air temperature

(b) Change in annual mean precipitation



(c) Atmospheric meridional overturning circulation

(d) Zonally averaged annual mean precipitation

Figure 6. Annual mean changes (water hosing minus control) in (a) near-surface air temperature, (b) precipitation, (c) atmospheric zonal mean meridional streamfunction, and (d) zonal mean precipitation change: in black the control climatology, in blue the water hosing anomaly. From Bellomo et al. (2023).

We calculated changes in the atmospheric moisture budget and weather regimes in the water hosing experiment. We find that, while precipitation decreases over most of the Euro-Atlantic sector, in some regions, the number of wet days increases following a decline of the AMOC, especially over north-western Europe. The moisture budget framework revealed that changes in the dynamics of the atmosphere, particularly the enhancement of the mid-latitude jet stream and its eastward extension towards north-western Europe, explain the increase in wet days anomalies. On the other hand, transient eddies are responsible for the drying. Although storm tracks are enhanced, their moisture is reduced, resulting in drier storms, even if more intense. The analysis of changes in weather regimes revealed an increase in the persistence and frequency of occurrence in NAO + events. For details on the impacts of a weakened AMOC on precipitation over the Euro-Atlantic region, the reader is referred to Bellomo et al. (2023).

Part 2

In light of the previous results, we decided to run a set of new experiments with the aim of deepening our understanding of the climate impacts due to a reduction of the AMOC. The new experiments consist of several ensemble members of AMIP (atmospheric only) runs to better disentangle the internal variability. This allows us to increase the number of daily outputs to perform statistical analysis oriented to the study of extreme events. From the uniform water hosing experiment, we selected slices of 10 years each from different mean AMOC index values, as indicated in Figure 7. The sea surface temperature (SST) and sea-ice cover from the 10 years time slices (Figure 8) were used as boundary conditions for a set of AMIP experiments. This way, 20 ensemble members (generated by a small perturbation to the initial condition) were run for three different mean AMOC index values: 17 (corresponding to the *piControl*), 14, and 7 Sv, approximately.

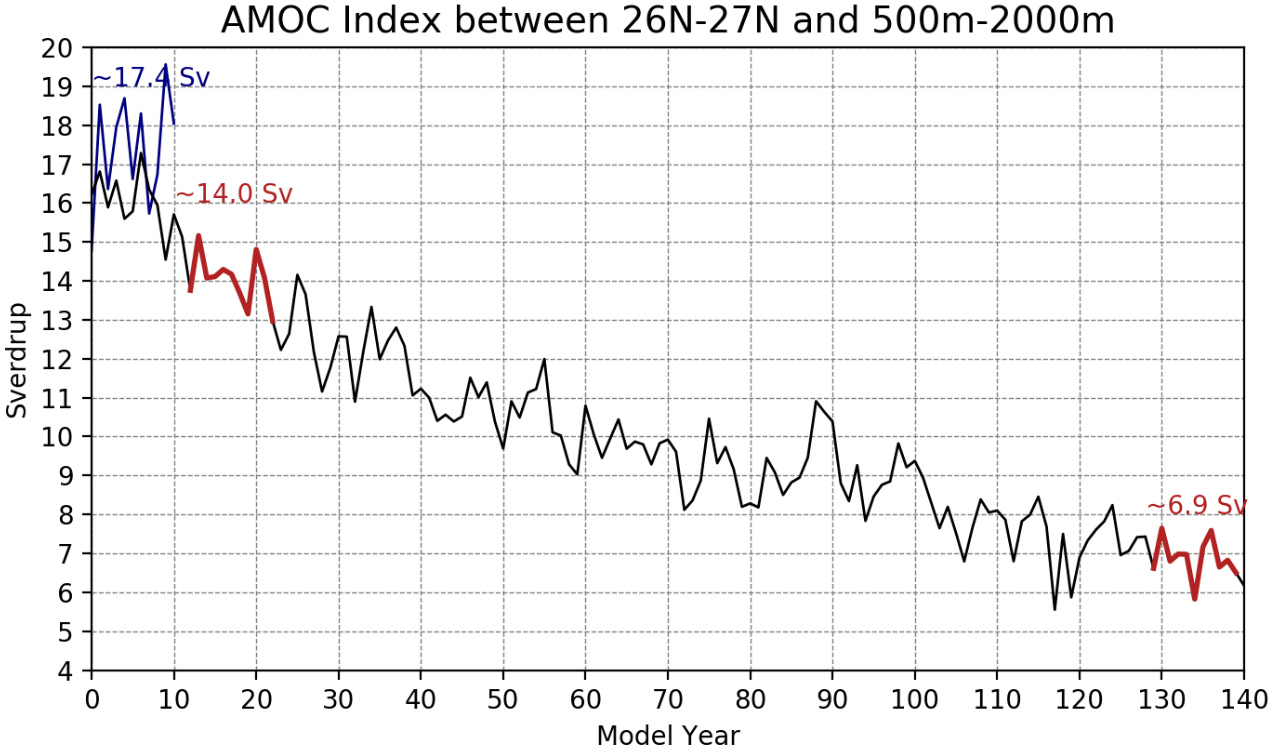


Figure 7. Time-series of the AMOC index in 140 years of the water hosing experiments. The 10-year slices selected as boundary conditions are highlighted in red.

We are currently analysing the results of the new set of simulations. Specifically, we are looking at the extreme events of temperature in Europe. So far, we have found that, although the mean climate in Europe is colder under a reduced AMOC due to the reduced northward heat transport, the cold spell duration index (CSDI) is reduced in north and eastern Europe. The CSDI is defined as the annual count of days with at least six consecutive days when the minimum temperature is lower than the 10th percentile of the daily climatology. The mean CSDI for the three ensembles and the difference with respect to the control are plotted in the left and right columns of Figure 9, respectively. These results are associated with a less amount of blocked days in winter under a reduced AMOC that can be linked to a stronger jet stream due to an increased temperature meridional gradient. We are still investigating the extreme temperature events in maximum temperature during boreal summer.

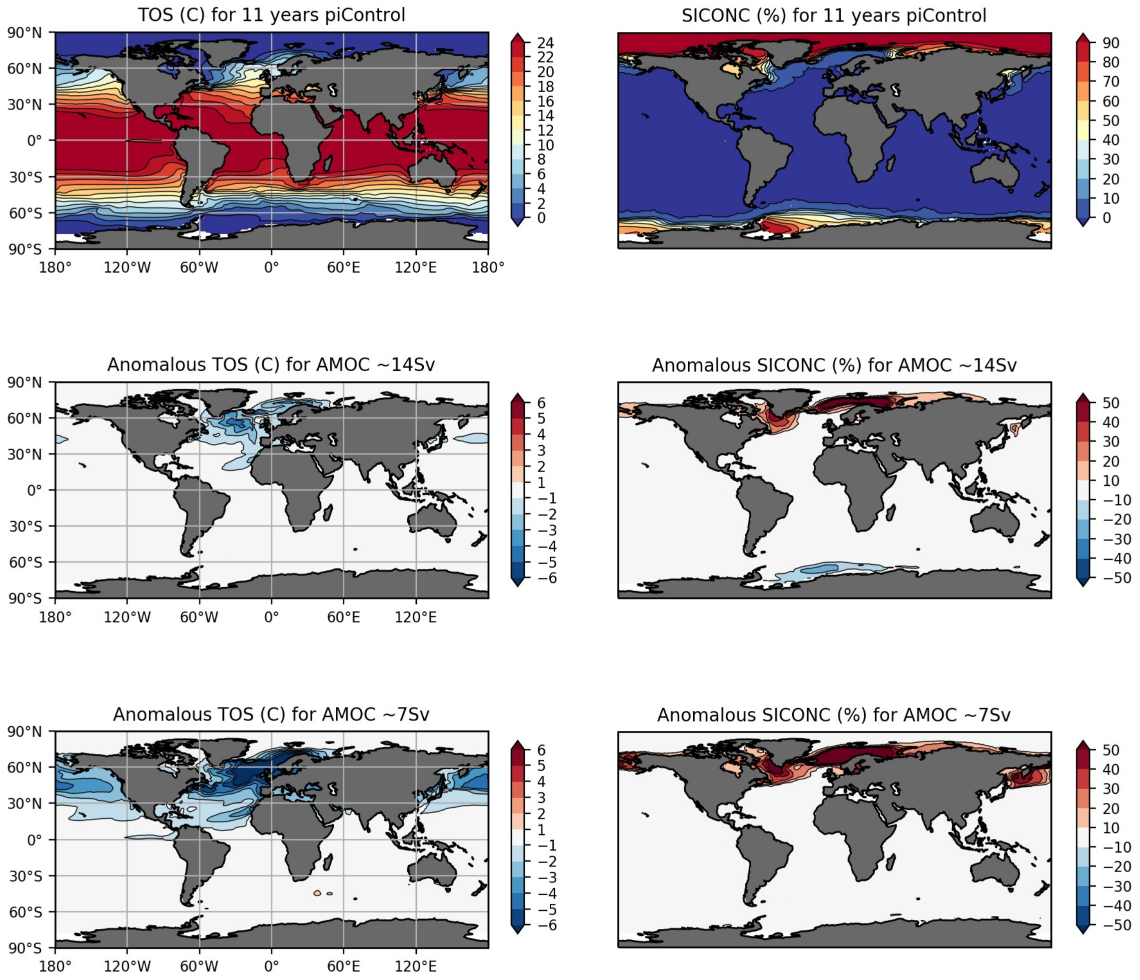


Figure 8. SST (left column) and sea-ice cover (right column) climatology of the 10-year time slices used as boundary conditions for the AMIPs simulations. The first row shows the absolute values from the piControl, while the second and third rows show the anomaly with respect to the control.

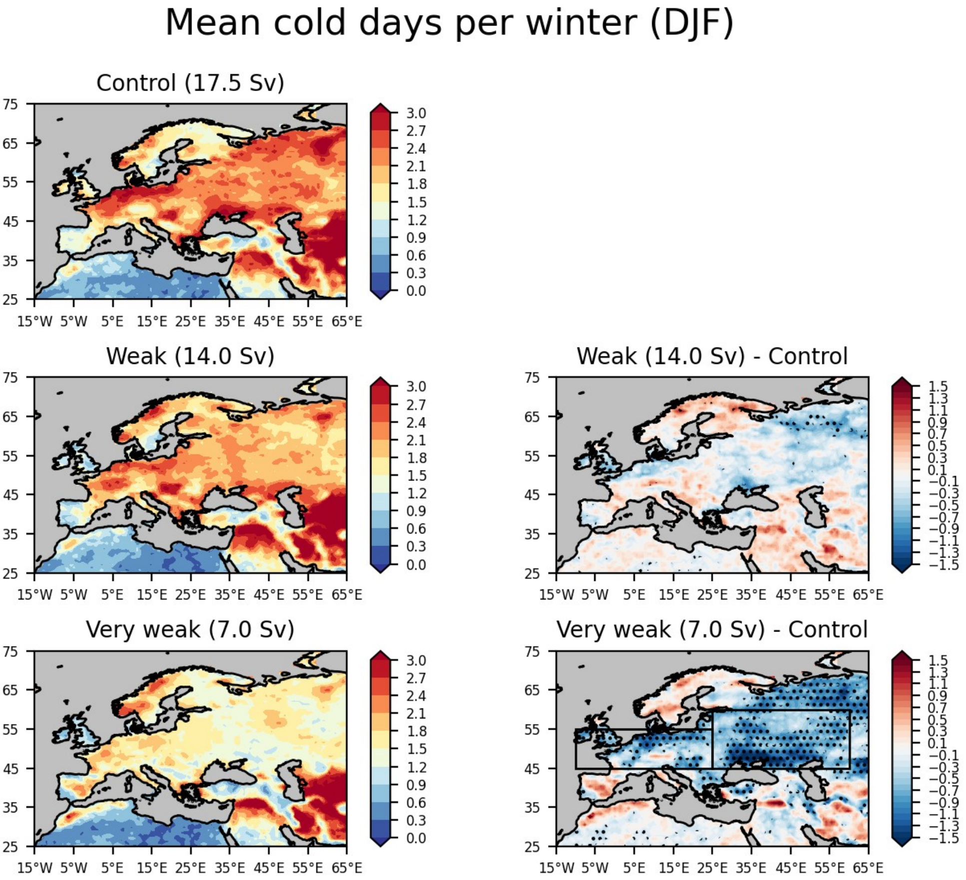


Figure 9. Mean cold spell duration index CSDI for the three ensembles (left column) and the difference with respect to the control (right column). Dots are plotted when 75% of the ensemble members have the same sign as the ensemble mean

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Clement, A. C., & L. C. Peterson (2008). Mechanisms of abrupt climate change of the last glacial period. Reviews of Geophysics, 46(4):RG4002. https://doi.org/10.1029/2006rg000204

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McManus, J. F, R. Francois, J. M. Gherardi, L. D. Keigwin, & S. Brown-Leger (2004). Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. Nature 428, 834–837. https://doi.org/10.1038/nature02494

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Rahmstorf, S. (2002). Ocean circulation and climate during the past 120,000 years. Nature, 419(6903), 207–214. https://doi.org/10.1038/nature01090

List of publications/reports from the project with complete references

a) Peer-reviewed journals

- Jackson, L.C., E. Alastrué de Asenjo, K. Bellomo, G. Danabasoglu, H. Haak, A. Hu, J. Jungclaus, W, Lee, V.L. Meccia, O. Saenko, A. Shao and D. Swingedouw. 2023. Understanding AMOC stability: the North Atlantic Hosing Model Intercomparison Project. Geoscientific Model Development, 16, 1975–1995, https://doi.org/10.5194/gmd-16-1975-2023

- Bellomo K., V.L. Meccia, R. D'Agostino, F. Fabiano, S.M. Larson, J. von Hardenberg and S. Corti. 2023. Impacts of a weakened AMOC on precipitation over the Euro-Atlantic region in the EC-Earth3 climate model. Climate Dynamics. https://doi.org/10.1007/s00382-023-06754-2

b) International conferences

- D'Agostino R., Bellomo K., and Meccia V. 2023. The impact of AMOC weakening on the global monsoon in EC-Earth3 water hosing simulations, EGU General Assembly 2023, EGU23-535, https://doi.org/10.5194/egusphere-egu23-535.

- Bellomo K., Meccia V., D'Agostino R., Fabiano F., Larson S., von Hardenberg J., and Corti S. 2023. Impacts of a weakened AMOC on the European climate, EGU General Assembly 2023, EGU23-5775, https://doi.org/10.5194/egusphere-egu23-5775.

- Bellomo K., Meccia V., D'Agostino R., Fabiano F., von Hardenberg J., and Corti S. 2022. The climate impacts of an abrupt AMOC weakening on the European winters, EGU General Assembly 2022, EGU22-1023, https://doi.org/10.5194/egusphere-egu22-1023.

- Jackson L., Alastrue-De-Asenjo E., Bellomo K., Danabasoglu G., Hu A., Jungclaus J., Meccia V., Saenko O., Shao A., and Swingedouw,D. 2022. AMOC thresholds in CMIP6 models: NAHosMIP, EGU General Assembly 2022, EGU22-2778, https://doi.org/10.5194/egusphere-egu22-2778.

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

We want to exploit the data produced during the second year of the project to deepen our knowledge of the implications of a weakened AMOC on regional climates. For the moment, we are not planning to run new experiments on this.